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# Insights into the development of electrokinetic remediation technology: A bibliometric analysis

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**Abstract:** Electrokinetic remediation (EKR) is a powerful technique aimed at pollutant removal in soil, sludge, mine tailings, and so on. In the current work, we performed a bibliometric analysis of the research on EKR for the period of 1900–2018 on the basis of the core database of the Science Citation Index Expanded. In addition to a basic analysis of the research characteristics, keywords were analysed for four major participants: USA, China, Spain, and South Korea. The periods of 1990–2001, 2002–2008, and 2009–2018 were studied using the keyword analysis method to gain insights into the development of EKR and predict its future trends. The results revealed that the related research field in the USA was broad during the study periods. Meanwhile, China was interested in fluorine pollution and contamination in red soil. Spain paid close attention to pollution due to agricultural contamination. South Korea focused on radioactive element pollution. The number of papers published over a period of 28 years increased steadily and continued to rise after 2008. The combined techniques of EKR + phytoremediation and EKR + bioremediation were successively utilised by scholars over time, and the latter is expected to demonstrate vitality in the future.

**Keywords:** bibliometrics; EKR; electrokinetics; remediation technology

Human activities generate large volumes of waste and pollutants as a result of rapid industrialisation. As an open and crucial system in the environment, the soil is forced to accept waste and pollutants and, thus, poses a huge threat to humans and the environment (Chen & Mei 2013).

A number of approaches have been applied to curb soil pollution, and they include soil leaching (Baes & Sharp 1983), soil flushing (Wasay et al. 2001), soil vapour extraction (Shan et al. 1992), thermal desorption (Vinegar & Stegemeier 2002), and bioremediation (Vidali 2001). In recent years, electrokinetic remediation (EKR) has drawn increasing research attention because of its low cost and high processing efficiency (Diana et al. 1990; Acar et al. 1995; Virkutyt et al. 2002); apart from the soil, EKR is also widely studied in the context of remediation for slurries (Ugaz et al. 1994), mine tailings (Baek et al. 2009), and groundwater (Zhang et al. 2001). The existing research on EKR encompasses its mechanism (Acar & Alshawabkeh 1993; Virkutyt et al. 2002), application range, influence factors (Baraud et al. 1999; Lee & Yang 2000; Zhou et al. 2004; Kim et al. 2012), and models (Alshawabkeh & Acar 1996; AI-Hamdan & Reddy 2008). However, the development of this novel technique has not been comprehensively discussed. Bibliometrics was introduced in 1969 as a practical tool for scientific researchers to obtain a clear perspective of a particular field through figures and tables used in statistical analyses (Wang et al. 2019), including research trends and hotspots and scientific institution distribution (Pritchard 1969). Moreover, researchers could obtain valuable information via data processing in bibliometrics (Li et al. 2019).

In the current work, we performed an elaborate bibliometric analysis to explore the development of

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EKR on the basis of the core database of the Web of Science from 1900 to 2018; this database is considered to be the largest and most comprehensive and influential academic informational source. The general characteristics of EKR were analysed, and the global research trends were summarised.

## MATERIAL AND METHODS

**Research scope.** The data were collected in the core database of the Web of Science, that is, the Science Citation Index Expanded (SCIE), on March 12, 2019. EKR has three mechanisms: electromigration, electrodialysis/electroosmosis, and electrophoresis/cataphoresis (Liu et al. 2018). Herein, the search topic was electrokinetic* remediation* or electromigration* remediation* or electrodialysis* remediation* or electroosmosis* remediation* or electrophoresis* remediation* or cataphoresis* remediation*; the asterisk (*) here means that the following content of the search topic can be arbitrary. Other parameters were kept unchanged; for example, the time span comprised all years from 1900 to 2018.

**Research method**. In terms of the political systems, papers from England, Scotland, Northern Ireland, and Wales were defined to be from the United Kingdom (UK); those from Hong Kong and Macau were regarded to be from mainland China, while papers from Taiwan were separated from mainland China.

To ensure a comprehensive understanding of EKR and given that the keyword(s) could directly reflect research hotspots, we comprehensively analysed the keywords across three periods: 1990–2001, 2002–2008, and 2009–2018. In addition, the bibliometric analysis was carried out on the basic characteristics of the existing EKR research to gain insights into the development regularity of EKR and predict any research trends. The theme keywords ("electrokinetic(s)," "electrokinetic remediation," and "electroremediation and remediation") were ignored, and similar keyword(s) were bracketed together ("soil, soils, soil remediation, and contaminated soil"; "heavy metal and heavy metals"; and "clay and clays").

## RESULTS AND DISCUSSION

**Analysis of the basic characteristics of the EKR literature.** A total of 1 562 papers were initially analysed to obtain the statistics of their basic characteristics. Table 1 shows the document types of the research reports. Nine document types were established, and the article type was the most frequently identified, making up over 80% of the total. By contrast, the figures for the editorial material, review; book chapter, article: early access, and corrections were all below 1%. The proportions of the articles: early access and corrections were the lowest, only representing 0.06% of the total.

Table 1. Document types of the research reports

| Document type | No. | (%) |
|---|---|---|
| Article | 1 276 | 81.69 |
| Article; proceedings paper | 172 | 11.01 |
| Review | 84 | 5.38 |
| Meeting abstract | 19 | 1.22 |
| Editorial material | 6 | 0.38 |
| Review; book chapter | 3 | 0.19 |
| Article; early access | 1 | 0.06 |
| Correction | 1 | 0.06 |
| Total | 1 562 | 100 |

The language types of the research reports were studied. Table 2 illustrates a one-sided state, that is, English was the dominant language type, with over 99% of the papers being written in English and only less than 0.5% being written in other languages; German, French, Russian, Chinese, Polish, and Portuguese language types only had one paper each. Hence, writing academic papers in English has become the mainstream trend for researchers.

Table 3 shows the ten most productive journals from 1990 to 2018. The Journal of Hazardous Materials was the only journal that published over 100 papers related to EKR (155), which accounted for 9.92% of the total number of published papers. Although the number of papers published in Chemosphere and Electrochimica Acta were similar (89 and 84, respec-

Table 2. Language types of the research reports

| Language type | No. | (%) |
|---|---|---|
| English | 1 548 | 99.10 |
| Spanish | 6 | 0.38 |
| Japanese | 2 | 0.13 |
| German | 1 | 0.06 |
| French | 1 | 0.06 |
| Russian | 1 | 0.06 |
| Chinese | 1 | 0.06 |
| Polish | 1 | 0.06 |
| Portuguese | 1 | 0.06 |
| Total | 1 562 | 100 |

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Table 3. Analysis of the journal titles (top 10)

| Title | No. | (%) |
|---|---|---|
| Journal of Hazardous Materials | 155 | 9.92 |
| Chemosphere | 89 | 5.70 |
| Electrochimica Acta | 84 | 5.38 |
| Environmental Science and Pollution Research | 50 | 3.20 |
| Separation and Purification Technology | 49 | 3.14 |
| Separation Science and Technology | 43 | 2.75 |
| Journal of Environmental Science and Health Part A | 37 | 2.37 |
| Environmental Science & Technology | 34 | 2.18 |
| Chemical Engineering Journal | 33 | 2.11 |
| Water Air and Soil Pollution | 28 | 1.79 |

Table 4. Contribution analysis of the academic institutions (top 10)

| Institution (country) | No. | (%) |
|---|---|---|
| Chinese Academy Science, China | 99 | 6.34 |
| University Castilla La Mancha, Spain | 85 | 5.44 |
| Technical University of Denmark, Denmark | 69 | 4.42 |
| University of Illinois, USA | 58 | 3.71 |
| Chongqing University, China | 50 | 3.20 |
| University of Vigo, Spain | 48 | 3.07 |
| Chonbuk National University, South Korea | 46 | 2.94 |
| University Nova de Lisboa, Portugal | 39 | 2.50 |
| National Sun Yat-Sen University, Chinese Taiwan | 27 | 1.73 |
| University Malaga, Spain | 26 | 1.66 |

tively), these numbers represented only about half of the number of papers published in the Journal of Hazardous Materials. The proportions of the papers published in other journals were all below 5%. Only 1.79% of the papers related to EKR were published in Water, Air, and Soil Pollution.

Table 4 presents the numbers of papers published by different academic institutions. This index could reflect the degree of participation for a specific academic institution. The Chinese Academy Science (China), University Castilla La Mancha (Spain), Technical University of Denmark (Demark), and University of Illinois (USA) published the most papers related to EKR; their papers made up nearly one-fifth of the total number. Hence, these four academic institutions played a dominant role in the field of EKR.

**Analysis of countries contribution and their research features for EKR**. Table 5 shows the numbers of papers published by different countries/districts. The USA, China, Spain, and South Korea published the most papers, which represented 60.05% of the total. Therefore, these four countries were major branches of EKR research.

The distribution of the EKR research was clarified by studying the keywords originating from the published papers from the USA, China, Spain, and South Korea. The results are shown in Table 6. The top keywords across the four countries were "soil(s)/soil remediation/contaminated soil" and "heavy metal(s)". Moreover, the four countries, except for South Korea, widely used the combined techniques of "EKR + bioremediation" and "EKR + phytoremediation". The research field for the USA was broad and ranged from bioremediation to phytoremediation, from soil to clay(s) to kaolin, and from inorganic (lead) to organic (PAHs, phenanthrene). These results verified the critical role of the USA in EKR research. The other countries presented distinct characteristics. On the one hand, China focused on the removal of heavy metals, especially cadmium, chromium, lead, and copper. On the other hand, scholars in China paid attention to fluorine pollution and contamination in red soil. Fluorine is derived from aluminium metallurgy, phosphate ore processing, phosphate fertiliser production, steel making, and coal burning. Luo et al. (2011) reported that people in southwestern China suffer from serious fluorine pollution. Red soil is widely distributed in south China where the population and the gross domestic product account for a large part of the whole country (Zhang et al. 2009). Therefore, the emergence of "fluorine" and "red soil" revealed the attempt of researchers to control pollution problems via EKR. As for Spain, the results of the keywords of "herbicide", "PAHs",

Table 5. Contribution analysis of countries (top 10)

| Country/District | No. | (%) |
|---|---|---|
| USA | 328 | 21.00 |
| China | 324 | 20.74 |
| Spain | 150 | 9.60 |
| South Korea | 136 | 8.71 |
| Taiwan | 72 | 4.61 |
| Denmark | 68 | 4.35 |
| Italy | 66 | 4.23 |
| UK | 62 | 3.97 |
| Australia | 59 | 3.78 |
| Portugal | 54 | 3.46 |

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Table 6. Keyword analysis for the four major countries

| USA | No. | China | No. | Spain | No. | South Korea | No. |
|---|---|---|---|---|---|---|---|
| Soil(s)/soil remediation/ contaminated soil | 48 | soil(s)/soil remediation/ contaminated soil | 66 | soil(s)/soil remediation/ contaminated soil | 41 | heavy metal (s) | 19 |
| Heavy metal(s) | 28 | heavy metal(s) | 41 | heavy metal(s) | 20 | soil(s)/soil remediation/ contaminated soil | 13 |
| Clay(s) | 22 | microbial community | 16 | herbicide | 9 | arsenic | 11 |
| Bioremediation | 10 | cadmium | 14 | PAHs | 8 | removal efficiency | 11 |
| Electroosmosis | 9 | bioremediation | 12 | oxyfluorfen | 8 | saline soil | 10 |
| Lead | 7 | chromium | 12 | bioremediation | 7 | caesium | 9 |
| Surfactants | 7 | electromigration | 8 | pilot plant | 7 | decontamination | 8 |
| Chromium | 5 | phytoremediation | 8 | 2,4-D | 7 | cobalt | 7 |
| Kaolin | 5 | lead | 6 | citric acid | 6 | electromigration | 6 |
| PAHs | 5 | copper | 6 | electrokinetic soil flushing | 6 | fractionation | 6 |
| Phenanthrene | 5 | sludge | 6 | natural soil | 6 | field application | 6 |
| Phytoremediation | 5 | fluorine | 6 | phenanthrene | 5 | surfactant | 5 |
| Zeta potential | 5 | red soil | 6 | electro-bioremediation | 5 | uranium | 5 |

"oxyfluorfen", "2,4-D" and "natural soil" revealed the country's focus on decontamination from agricultural pollution. Spain is an agricultural country, and its farming techniques are the best globally, hence the result. By contrast, researchers in South Korea showed great interest in the removal of radioactive elements (caesium and uranium), in addition to arsenic and cobalt, via EKR.

**Analysis of development regularity for EKR**. Figure 1 shows the annual growth trend of the number of published papers on EKR. The first research paper related to EKR was published in 1990. This result confirmed that EKR is a relatively novel technique. The 28-year period witnessed a steady growth for EKR, which indicated the increasing attention being paid to EKR. The number of related papers published after 2018 continued to rise steadily according to the result of the fitting line because of the enormous potential of EKR.

Three different growth trends for EKR papers published per year are provided in Figure 1. The periods of 1990–2001, 2002–2008, and 2009–2018 were characterised by different development regularities for EKR.

Table 7 presents the analysis of the keyword(s) and their frequencies in the different periods. The keywords of "soil(s)/soil remediation/contaminated soil" and "heavy metal(s)" were the most popular across all the periods. This peculiarity can be attributed to the severity of the pollution. The keywords "clay(s)" and "kaolinite" also received much attention (8 and 7) from 1990 to 2001, after which "kaolinite" and "clay(s)" disappeared successively in the second and third periods. By contrast, "lead" received the most attention over a period of 28 years. As "soil(s)/soil remediation/contaminated soil" and "heavy metal(s)" had the largest number of related research, one could infer that soil pollution and heavy metal pollution received much attention and could be expected to become a research hotspot in the future. In addition, researchers clearly showed great interest in inorganic

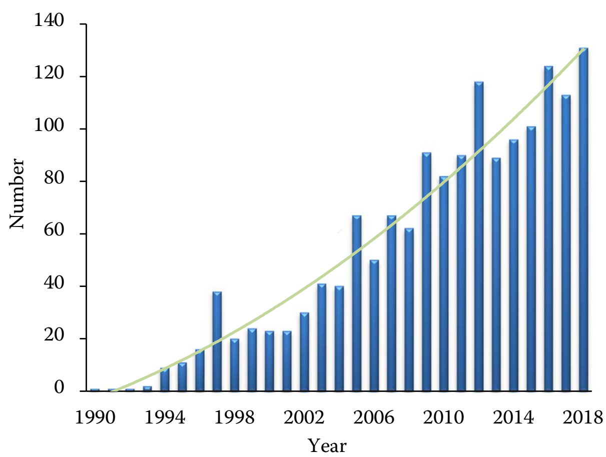


Figure 1. Annual growth trend of the number of published electrokinetic remediation (EKR) papers; the fitting equation is $y = 0.0788x^2 - 311x + 306909$ and $R^2 = 0.9495$

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Table 7. Keyword analysis for the three different growth periods

| 1990–2001 | No. | 2002–2008 | No. | 2009–2018 | No. |
|---|---|---|---|---|---|
| Soil(s)/soil remediation/ contaminated soil | 30 | soil(s)/soil remediation/ contaminated soil | 93 | soil(s)/soil remediation/ contaminated soil | 178 |
| Heavy metal(s) | 17 | heavy metal(s) | 52 | heavy metal(s) | 139 |
| Clay(s) | 8 | clay(s) | 20 | bioremediation | 54 |
| Electromigration | 8 | electroosmosis | 17 | phytoremediation | 30 |
| Kaolinite | 7 | phenanthrene | 14 | lead | 29 |
| Lead | 5 | copper | 14 | chromium | 26 |
| Groundwater | 5 | lead | 12 | microbial community | 24 |
| Cadmium | 5 | chromium | 12 | electromigration | 24 |
| Electroosmosis | 5 | electromigration | 11 | DGGE | 23 |
| Soil pH | 4 | cadmium | 11 | sediment | 22 |

pollution between 1990 and 2001. In 2002, scholars began attempting to curb contamination caused by organic phenanthrene through EKR. After 2008, the technology of EKR made great progress. This technique yielded two major branches: bioremediation and phytoremediation. The keyword of "microbial community" was studied by twenty-four papers. Denaturing gradient gel electrophoresis (DGGE), first appeared throughout the period. Bokulich and Mills (2012) reported that DGGE has been widely used in the field of microbial ecology in recent years due to its cost-effective nature. As shown in Figure 2, the number of papers published with the topics of "EKR + bioremediation" and "EKR + phytoremediation" remained on a low level before 2008, after which they obviously grew. While the technology of EKR + bioremediation had the largest number of papers during 1990–2018, except for 2004, both techniques of EKR + bioremediation and EKR + phytoremediation are expected to be attractive to researchers.

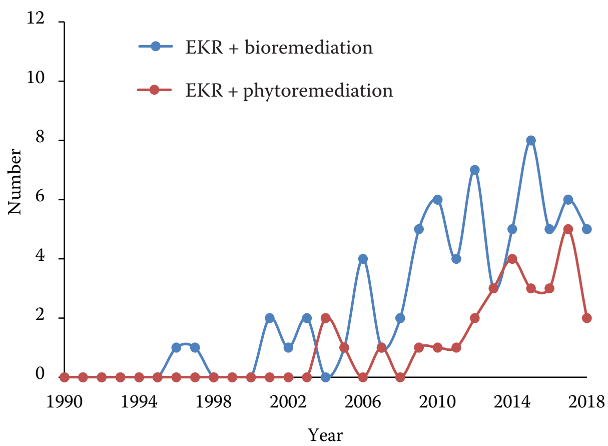


Figure 2. Annual growth curves of the electrokinetic remediation (EKR) + bioremediation and EKR + phytoremediation in the total number of papers during 1990–2018

## CONCLUSION

According to the bibliometric results for the EKR research, the following conclusions can be drawn.

(1) Over 80% of the published EKR papers are articles (81.69%). Most of the published papers were written in English, and they accounted for 99.10% of the total. The Journal of Hazardous Materials and the Chinese Academy of Sciences (China) published the most EKR papers (155 and 99, respectively).

(2) The research field of EKR in the USA was broad. China demonstrated interest in fluorine pollution and contamination in red soil. Spain paid close attention to pollution due to agricultural contamination. South Korea showed interest in radioactive element pollution.

(3) The combined techniques of EKR + phytoremediation and EKR + bioremediation were successively utilised by scholars across the study periods, and both techniques are expected to be attractive to researchers.

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